Superconducting Magnet Division

Magnet Note

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BNL MAGNET DIVISION NOTE 644-33

CONSTRUCTION AND TEST OF Nb_3Sn COMMON COIL MAGNET DCC017

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Summary

This note briefly reports construction features and test results for a common coil model dipole, DCC017. The cable was made from Oxford MJR Nb_3Sn strand. The cable was coated with Mobil1 oil and reacted prior to coil winding. Four racetrack coils were wound and vacuum impregnated. Stainless steel collars applied a modest preload only in the coil straight section and only perpendicular to the surface of the cable. The iron yoke and stainless steel shell limited coil strain perpendicular to the magnet aperture. Stainless steel end plates limited the coil axial strain to 0.2%. The coil overall length was 620 mm (24.4") and the usable coil aperture was 32 mm (1.25").

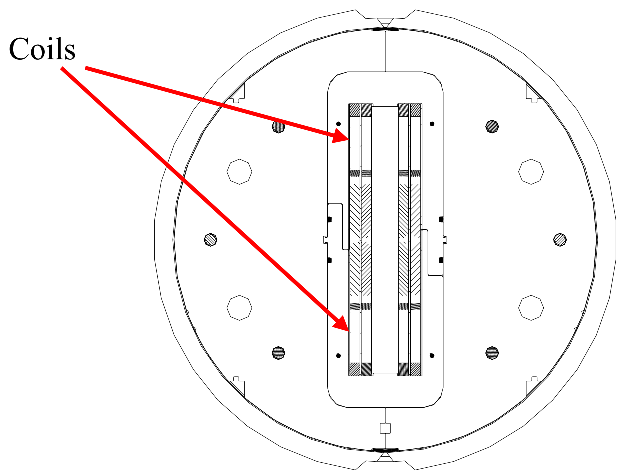
The highest quench of the magnet was at 10.8 kA, the expected limit of the conductor, corresponding to a calculated peak field of 10.8 T and a calculated central field of 10.3 T. After a thermal cycle, the magnet's lowest quench was at 9.2 kA (8.8 T central field). The conductor exhibited no dependence of quench current on ramp rate for ramps between 4 A/s and 200 A/s. Measured MIITS values were in general agreement with expectations that the magnet would be self-protecting.

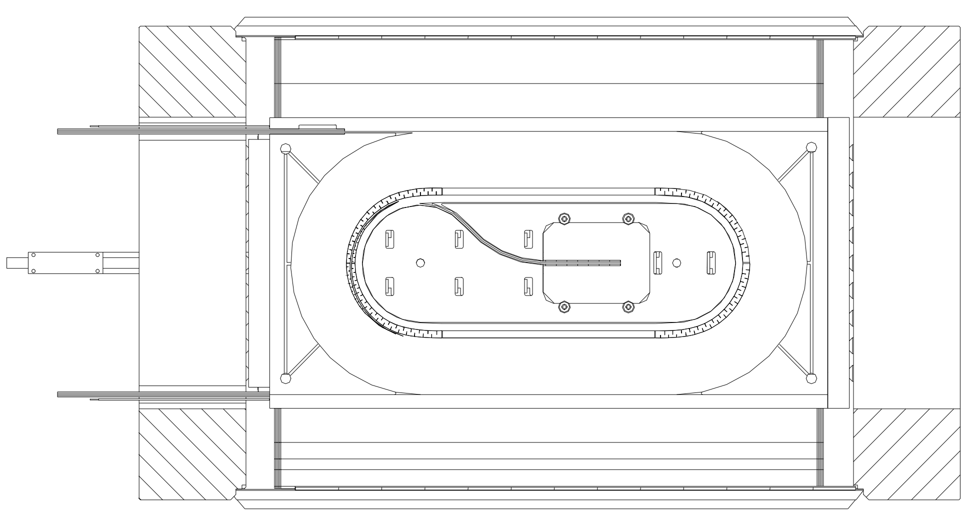
Arup Ghosh's summary of the conductor properties, John Cozzolino's summary of the magnet construction, and Joe Muratore's summary of the quench data are appendices.

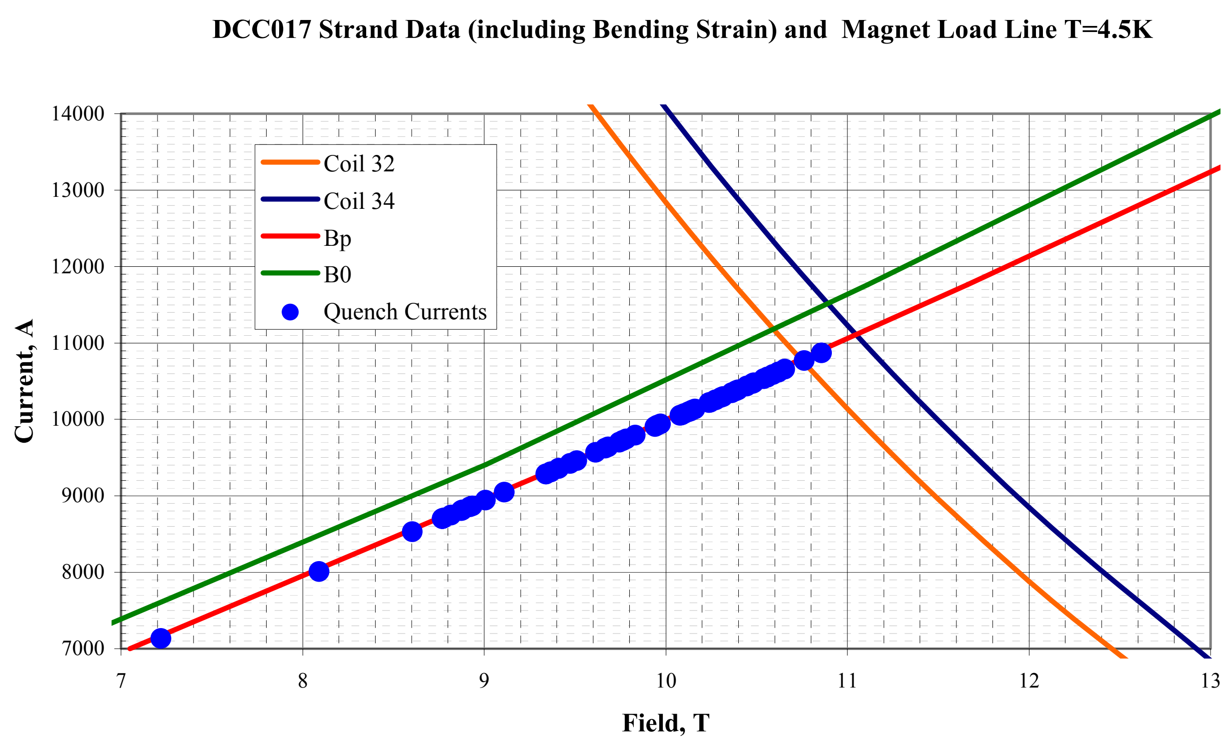
Test Results

Cross sections of the magnet are shown in Fig. 1 and 2. The magnet was tested during February, 2006, in a liquid helium bath at a nominal temperature of 4.5 K. Fig. 3 shows the calculated load line of the magnet for both peak and central fields, the quenches plotted on the peak field load line, and the short-sample limit of the conductor, based on strand tests (see appendix). Fig. 4 shows the quench history of the magnet. The threshold for detecting voltage spikes was 60 mV. Voltage spikes were seen during the ramp up and/or at the quench onset for many quenches. Quenches at the two highest currents were in coil 32, which was expected to reach its conductor limit before the other three coils. Ramp rates varied during the testing. A typical ramp profile was 25 A/s to 4 kA, then 3 A/s or 10 A/s to quench. For the ramp rate study (the last 15 quenches), the magnet was ramped at constant ramp rate to quench. The magnet was instrumented with voltage taps on the leads and at the splices between the coils. MIITS values were generally consistent with those expected based on calculations using the code QUENCH, which predicted that the maximum temperatures would be less than 400 K.

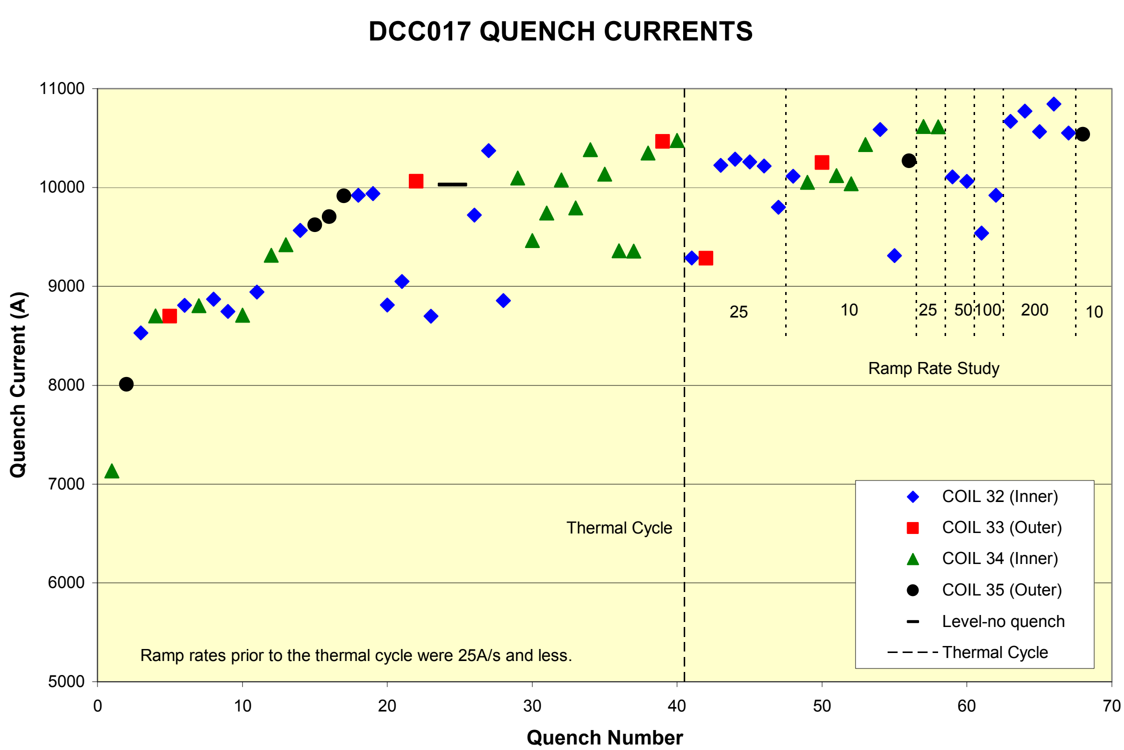
Acknowledgement. We wish to thank our technical staff for their careful work during the construction and testing of this magnet.







DCC017 Strand Data (including Bending Strain) and Magnet Load Line T=4.5K
Coil 32
Coil 34
Bp
B0
Quench Currents
Current, A
Field, T
14000
13000
12000
11000
10000
9000
8000
7000
7
8
9
10
11
12
13



DCC017 QUENCH CURRENTS
Quench Current (A)
Quench Number
11000
10000
9000
8000
7000
6000
5000
0
10
20
30
40
50
60
70
25
10
25
50
100
200
10
Ramp Rate Study
Thermal Cycle
Ramp rates prior to the thermal cycle were 25A/s and less.
COIL 32 (Inner)
COIL 33 (Outer)
COIL 34 (Inner)
COIL 35 (Outer)
Level-no quench
Thermal Cycle

Appendix:

DCC017-Conductor parameters and Critical Current

Arup K. Ghosh

Abstract

This note summarizes the strand and cable that were used for the common coil magnet DCC017. The short sample limit of the magnet is calculated from strand measurements.

Introduction

The testing of short samples of Nb3Sn cable has been a difficult task as the nature of this superconductor renders the cable susceptible to critical current degradation due to improper handling and mechanical stresses. For the purposes of comparing the magnet performance, critical currents of the cable were calculated from critical current measurements made on strands extracted from the cable.

Strand and Cable Parameters

DCC017 used 30-strand cable made from 0.8 mm diameter strand manufactured by Oxford-Instrument Superconducting Technology using the Modified Jelly-Roll (MJR) process. The Nb3Sn wire used came from two billets, ORE-163 and ORE-202. Both billets nominally have the same copper fraction of 60%. Coils for this magnet were made from two lengths of cable, one of which BNL-N-4-0012 (ORE-163) was fabricated in New England Wire Co. (NEW), whereas cable BNL-6-O-B0899R (ORE-202) was made at LBL. All cable lengths for the four coils were vacuum impregnated with Mobil1® , and pre-annealed at 200C for 8 hours to drive-off the volatile constituents in the oil and also to remove the strain in the copper. The cable sections were then reacted in the vacuum furnace using the following schedule: 48 hrs/200C + 48 hrs/400C + 72 hrs/665C. After reaction the cable dimensions are shown in Table 1. Coil 32 used cable BNL-N-4-0012. Coils 33, 34 and 35 used BNL-6-O-B0899R

Table 1

Cable ID	Cable Width (mm)	Cable Thickness Major (mm)	Cable Thickness Middle (mm)	Cable Thickness Minor(mm)
BNL-N-4-0012				
Coil #32	12.72	1.513	1.509	1.504
BNL-6-O-B0899R				
Coil #33,34,35	13.17	1.529	1.513	1.509

Strand Tests

Extracted strands from the cable were reacted on stainless-barrels using the same reaction schedule as the cable segments. Table 2 summarizes the critical current measurements in the range of 8 to 11.5T. The 12T value is obtained by fitting the data to the Summer's formulation for Jc-B-ε. The initial strain in the conductor is taken to be -0.16%.

Table 2

WireID	Cu_Non Cu	Bath Temp	Jc(12T)	Ic(12T)	Ic(11.5T)	Ic(11T)	Ic(10T)	Ic(9T)	Ic(8T)	RRR
ORE-163-ES	1.54	4.229	1795	355	395	440	542	957		46
ORE-202-ES	1.60	4.216	2030	393	434	482	590	710	852	62
ORE-202-ES	1.60	4.232	2025	391	433	481	585	707	848	60

The cable was reacted on a 280mm diameter drum. The bending strain experienced by the strand when the cable from the drum is straightened or when the cable is bent at radius of 70mm is identical. The effect of the bending is to increase the compressive strain in the strand by 0.21% to a maximum of -0.37%. Using Summers' formulation, the critical current of the cable is calculated for coils 32 and 33, 34 and 35. Since coil 32 is one of the inner coils, it will be the limiting coil when the magnet reaches the short sample limit. The calculated critical currents at 4.2K and the strain degraded current at 4.5K (magnet operating temperature) are shown in Table 3.

Table 3

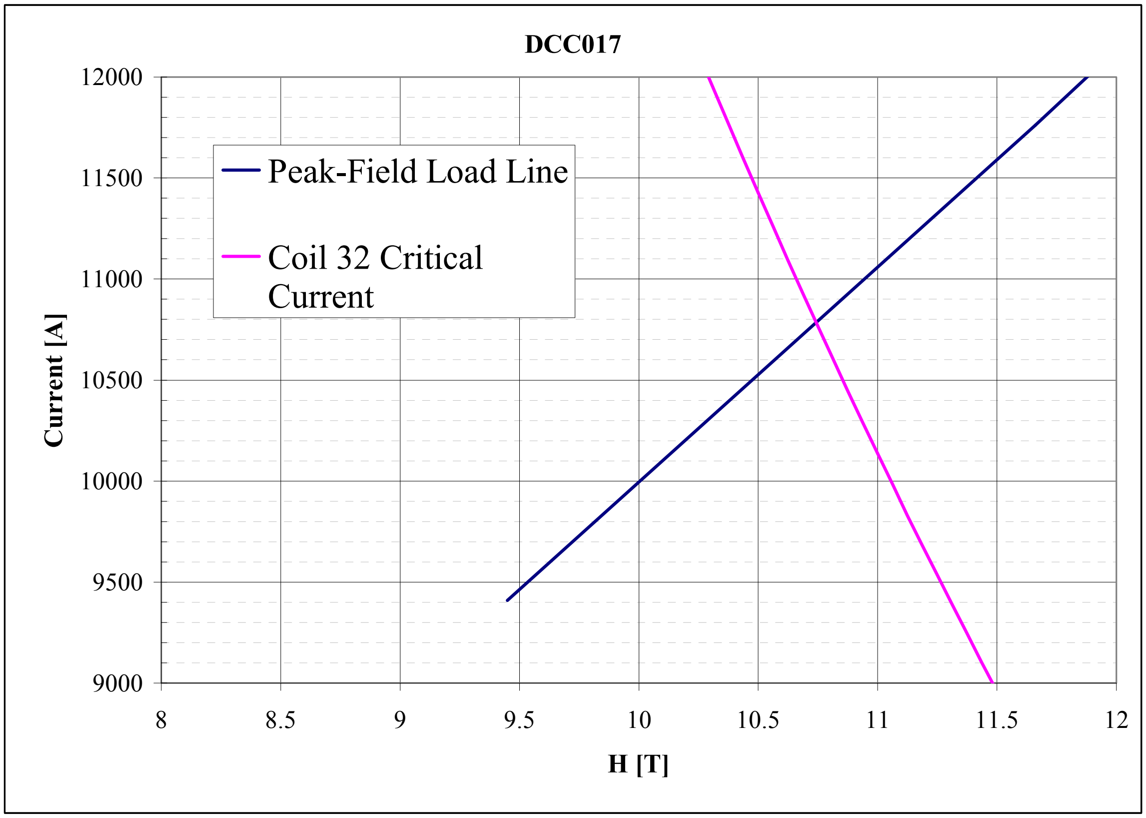
	Coil-32		Coil 33,34,35	
H, T	Ic(4.22K, -0.16%)	Ic(4.5K, -0.37%)	Ic(4.22K, -0.16%)	Ic(4.5K, -0.37%)
7.0	29216	24745	31160	26485
8.0	24050	19983	25793	21532
9.0	19710	16077	21348	17458
9.5	17970	14383	19404	15687
10.0	16260	12838	17618	14068
10.5	14649	11427	15975	12587
11.0	13188	10137	14462	11230
11.5	11820	8959	13065	9986
12	10650	7882	11776	8847

Using the calculations by R. Gupta for peak field (Table 4) the short sample limit of the magnet is calculated to be 10.8 kA

Table 4

B0	Bpk	I(cable)
T	T	A
9.01	9.45	9410
11.11	11.66	11760
13.13	13.8	14120

The plot below shows the load line and the critical current of the cable in coil 32 at a temperature of 4.5 K and a strain ε=-0.37%.



Appendix: ***10T Common Coil Magnet DCC-17 - J. Cozzolino 2/27/06***

This magnet, the first of its kind, is an outgrowth of the 10-turn react-and-wind Nb_3Sn coil program which has been ongoing at BNL. It has 1.25 in. of usable coil aperture that offers a background field of 10 Tesla for advanced cable testing. The plan is to operate this magnet in a vertical helium dewar while it is fitted with a 25kA cable sample holder. The sample holder shall be capable of applying a 20 kpsi warm assembly preload to straight and flat cable samples, and will be capable of resisting cable movement at full current, to within 0.2% strain.

The two pairs of coils in this magnet have been pre-reacted and wound on a 70mm diameter steel bobbin with a .007 inch thick nomex insulating separator. The utmost care was taken to avoid over-straining the cable. Winding tension did not exceed 12.0 lb. for the cable (15 lb for the nomex). No clamps or lacing was used during winding. The cable was permitted to make its natural transition from straight section to end. Therefore, the cable leaned over 7° as measured at the 45'th turn. No attempt was made to remove this condition due to overriding concerns regarding possible conductor damage. A relatively gentle 50 lb force was applied to the straight section of the coil to set its width and requisite shimming against the bobbin. All shims were tapered at the ends of the straight section to follow the shape of the cable turn.

The end and side saddles are made of stainless steel and have been custom fitted to each individual coil. No pre-compression was applied during coil impregnating or curing. All large voids were filled with fiberglass or G-10. Each coil was checked for straightness and flatness after curing. The coils have been pinned into pairs and shimmed to equal overall size with alumina filled epoxy. In between the layers of each coil pair is a .065 in. thick stainless steel sheet to aid in stress distribution at full power. Four .001 in. thick stainless steel strip heaters have been insulated with kapton and fitted to both sides of this sheet. Installed between each paired coil assembly, they are used for quench protection.

A collaring press was been built specifically for this magnet. It is sufficiently massive and stiff in order to maintain coil bending and/or twisting to safe levels. Coil prestress was strictly in the side-to-side direction (cable stack direction) and was relatively low (2.5 kpsi). An inflatable bladder was employed to maintain the coils hard outward against the collars during collaring. Stainless steel "keepers" were installed for the purpose of locking the coils against the collars.

The laminated iron yoke, along with the 1 inch thick stainless steel shell serves to support the collars at mid-span in resisting the lateral Lorentz forces generated by the coils. Axial strain due to the end Lorentz forces has been kept to within 0.2% by the five inch thick end plates.

Refer to the basic construction features listed below:

10T Common Coil Magnet DCC-17 Construction Features	
Number of coils	4
Conductor Type	Nb_3Sn React and Wind
Coil OAL	24.4 in.
Coil Straight Section Length	12 in
Coil Inside Radius	2.75 in.
Coil Outside Radius	6.1 in.
Coil Conductor Width	.501 - .517 in.
Number of Turns	45
Coil Curing Preload - Sides	0
Coil Curing Preload – Ends	0
Cable Insulation	Nomex 410, .007 in. thick
Coil Bobbin (Core) Material	Carbon Steel
Potting Agent	Stycast CTD-101K
Central Field	10 Tesla
Driving Current	10.8 kA
Yoke Length	25.7 in.
Yoke Weight	1750 lb.
Yoke O.D.	21 in.
Aperture	13.3 in. x 1.245 in.
Warm Collaring Preload – Sides	2.5 kpsi
Warm Collaring Preload – Ends	0
Collar Material	Kawasaki High-Mn SST
Bladder Pressure	40 psi
End plate Thickness	5 in.
Collar Key Type	Phosphor Bronze Tapered
Total Magnet Weight	3850 lb.
Coil Hypot Limit	1 kV

3-Mar-2006
J. F. Muratore
Brookhaven National Lab

DCC017 QUENCH SUMMARY

Dewar #6
Top Hat – Common Coil
I_{ss} ~ 10800A
Coils 32 and 34 are inner coils
Coils 33 and 35 are outer coils

QUENCH #	RUN #	CURRENT (A)	Ramp Rate (A/s)	T (K)	Press (psi)	START (ms)	MIITS	COIL	COMMENTS
T = 4.5K (nom)									
1	11	7132	20	4.442	17.77	-67	15.4	34	spikes (d)
2	12	8008	10	4.478	17.88	-59	16.7	35	no spikes
3	13	8530	10	4.541	19.32	-33	15.3	32	spikes
4	14	8700	10	4.541	19.38	-34	16.2	34	spike
5	15	8699	10	4.542	19.23	-57	18.0	33	spike,sp at start
6	16	8809	10	4.542	19.38	-26	14.9	32	spike,sp at start
7	17	8806	10	4.546	19.33	-29	15.5	34	no spikes
8	18	8869	10	4.541	19.32	-28	15.7	32	no spikes
9	19	8747	10	4.561	19.61	-32	15.7	32	no spikes
10	20	8709	10	4.562	19.50	-23	14.7	34	no spikes
11	21	8943	10	4.558	19.51	-32	15.9	32	spikes

12	22	9315	10	4.562	19.28	-24	15.5	34	no spikes
13	23	9423	10	4.560	19.32	-35	17.0	34	no spikes
14	24	9567	10	4.561	19.44	-14	14.8	32	no spikes
15	25	9622	10	4.559	19.31	-26	16.5	35	spike
16	26	9703	10	4.547	19.31	-23	16.2	35	spikes
17	27	9914	10	4.564	19.72	-27	16.8	35	spikes
18	28	9921	10	4.577	19.65	-25	16.2	32	spike
19	29	9938	10	4.577	19.83	-21	15.7	32	no spikes
20	30	8813	10	4.578	19.69	-20	14.9	32	spike
21	31	9049	10	4.560	19.57	-26	15.6	32	no spikes
22	32	10062	10	4.535	19.60	-40	18.0	33	no spikes
23	33	8699	10	4.529	19.66	-27	15.3	32	no spikes
	34	10028	10	NO QUENCH; RAN AT 10028 FOR 10 minutes					
	35	10028	10	NO QUENCH					
24	35	9723	25	4.557	19.25	-19	15.4	32	spikes
25	36	10372	10	4.544	19.27	-10	12.2	32	spikes
26	37	8855	10	4.538	19.22	-26	14.3	32	no spikes
27	39	10097	10	4.555	19.35	-29	17.2	34	spike
28	40	9462	10	4.541	19.28	-28	16.6	34	spike

29	41	9742	10	4.543	19.22	-32	17.2	34	no spikes
30	42	10076	10	4.531	19.17	-23	16.8	34	no spikes
31	43	9794	10	4.556	19.38	-22	16.2	34	spike,sp at start
32	44	10384	3	4.534	19.41	-12	12.1	34	no spikes
33	45	10136	3	4.555	19.34	-14	13.7	34	no spikes
34	46	9359	3	4.545	19.45	-18	14.3	34	no spikes
35	47	9356	25	4.551	19.35	-20	15.1	34	no spikes
36	48	10348	25	4.548	19.28	-23	16.8	34	spike
37	49	10467	25	4.526	19.48	-40	19.1	33	spikes,sp at start
38	50	10475	25	4.542	19.50	-26	17.4	34	spikes

Thermal Cycle
T = 4.5K (nom)

39	52	9286	25	4.558	19.55	-15	14.0	32	spike,sp at start
40	53	9284	25	4.379	19.41	-31	16.6	33	no spikes
41	54	10224	25	4.350	19.63	-16	13.1	32	spikes
42	55	10286	25	4.560	19.66	-12	14.6	32	spikes
43	56	10258	25	4.331	19.57	-14	12.8	32	spikes
44	57	10217	25	4.549	19.63	-31	10.9	32(i)	spikes (i)
45	58	9799	25	4.436	19.64	-22	15.8	32	spikes

46	60	10115	10	4.519	19.40	-20	10.6	32(j)	spikes (j,k)
47	61	10051	10	4.530	19.47	-27	16.1	34	spike,sp at start
48	62	10252	10	4.530	19.57	-40	18.2	33	spikes
49	63	10122	10	4.532	19.60	-12	12.9	34	spikes
50	64	10038	10	4.522	19.47	-13	13.5	34	no spikes
51	65	10435	10	4.525	19.47	-25	15.8	34	no spikes
52	68	10585	10	4.373	19.70	-14	14.4	32	no spikes
53	69	9311	10	4.519	19.66	-15	14.4	32	no spikes
54	70	10268	10	4.549	19.70	-19	15.2	35	spike

RAMP RATE STUDY

55	71	10619	25	4.551	19.73	-10	12.2	34	spikes
56	72	10615	25	4.533	19.67	-14	13.9	34	spikes
57	73	10107	50	4.501	19.64	-20	15.9	32	spikes
58	74	10062	50	4.535	19.61	-22	16.4	32	spikes
59	75	9540(n)	100	4.553	19.64	-21	15.4	32	spikes
60	76	9921	100	4.402	19.28	-22	16.1	32	spikes
61	77	10670	200	4.529	19.63	-20	15.5	32	spikes (m)
62	78	10773	200	4.462	(l)19.89	-17	14.5	32	spikes (m)
63	81	10567	200	4.520	(l)19.29	-15	14.0	32	spikes (m)
64	82	10846	200	4.525	(l)19.39	-22	16.4	32	spikes (m)

65	83	10552	200	4.514	19.31	-14	15.0	32	spikes (m)
66	84	10537	10	4.526	19.39	-23	16.1	35	spikes

Notes:

a) Ramp rate for quench #1 was 50A/s to 4000A. Then ramp at 20A/s in 500A steps to quench.
Ramp rate for quenches 2-23, 25-31, and 46-54 was 25A/s to 4000A, then 10A/s to quench (standard ramp). For quench 31, two cycles 40-4000A at 25A/s were done before the standard ramp to quench. For quenches 52 and 54, there was a stop at 10000A for 5 min.
Ramp rate for quenches 32-34 was 25A/s to 4000A, then 10A/s to 8000, then
3A/s to quench.
Ramp rate for quenches 24, 35-45 was 25A/s to quench.
RAMP RATE STUDY:
Ramp rate for quenches 55-56 was 25A/s to quench.
Ramp rate for quenches 57-58 was 50A/s to quench.
Ramp rate for quenches 59-60 was 100A/s to quench.
Ramp rate for quenches 61-62 was 200A/s to quench.
Ramp rate for quenches 63-65 was 25A/s to 1000A, then 200A/s to quench.
Ramp rate for quench 66 was 25A/s to 4000A then 10A/s to quench.

b) The temperature sensor recorded was silicon diode TS4. It had a redundant sensor TS3 associated with it. They were located at the nonlead end (bottom)of the magnet. There were also a pair of diodes at lead end (bottom) of the magnet.

c) Data acquisition sampling rate was 1kHz for all quenches.

d) Spikes: "sp at start" means spike right at quench start.
"spike" or "spikes" mean one or more spikes were seen earlier than the quench start. These had to be spikes greater than 60mV to be seen above the noise level. "no spikes" means that no spikes greater than 60mV were seen previous to the quench start.

e) For quenches in coil 32, coil 34 also quenched later, typically very slowly at first, at −9ms to 0ms, then faster at about 80ms (sometimes this was sooner, at about 35ms).

f) For quenches in coil 34, coil 32 also quenched later.

g) For quenches in coil 33, coils 34 and 32 also quenched later.

h) For quenches in coil 35, coils 34 and 32 also quenched later.

i) Quench #44 had an unusual signature. Coils 32, 33, and 34 all started very slowly, at about −31ms; coils 32 and 34 both take off steeply, at about -13ms. Coil 32 resistance continues to steeply rise, while the other coils, including 34, decrease. This all takes place prior to strip heaters firing.
Also, spike activity was more pronounced than for this quench than typical.

j) Quench #46 had an unusual signature. Coils 32, 34, and 35 all started very slowly, at about –20ms; coils 32 and 35 both take off steeply, at about -3ms. Coil 32 resistance continues to steeply rise, while the other coils, including 35, decrease. This all takes place prior to strip heaters firing. Also, spike activity was more pronounced than for this quench than typical.

k) Starting with quench #46, the delay between the quench detector stop pulse and power supply shutoff was 16ms. Previous to this quench, the delay was about 58ms. This was done by inhibiting the power supply firing circuit. The delay was minimized in order to decrease the amount of heating in the coils after each quench.

l) Prior to quenches 62-64, there were relatively large pressure fluctuations.

m) Prior to quenches 61-65, there was high spike activity, including a spike wider than typical in quench 62.

n) For quenches 59-65, ramped at 100A/s and higher, quench current data displayed are from the fast data logger (LeCroy) Ch 101 current signals. These are the maximum current reads (except isolated noise spikes) and are corrected for the errors introduced by the isolation amplifier which the signal must go through before entering the logger. All other current data are the peak values obtained from the Fluke 8502A Meter which is too slow to give consistently correct readings at the high ramp rates, but has a more accurate voltage measurement than the logger.